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Report on

PRO-SUBMARINE PROGRAM OF SOUND DIVISION, NRL

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Foreword

There is well under way at the Naval Research Laboratory a comprehensive, promising, and vigorously prosecuted Pro-Submarine Sonar Research and Developmental Program that should be more widely recognized and understood within the Naval Service. The following paragraphs state in nontechnical language the aims and sketch the nature, content, and present status of this program.

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I. SCOPE AND CONTENT

1. The pro-submarine research and developmental program of the Sound Division of NRL, now well underway, has been gradually moulded to its present content through conversations with submarine officers having combat experience and a study of reports dealing with antisubmarine attack procedure. This program aims to:

a. Improve search by extending the listening range.

b. Strengthen attack by supplying better target range and bearing data and determining the course of the target.

c. Reduce the hazard imposed by mines and mine field by supplying improved ways and means of detecting and locating small objects.

d. Detect the presence and bearing of approaching torpedoes.

e. Help determine escape procedure by providing visual indication (PPI) of the bearing and approximate range of the attacking ship or ships.

2. The underlying reasons that have determined the nature and content of this program and a simple word description of the component parts follow in turn.

A. Increasing Search Range

3. Extension of the present submarine search range must be accomplished through improved ways and means of detecting by listening to the sound generated by the target, since a submarine cannot risk disclosing its presence and whereabouts by prolonged echo ranging. The approximate range to which a target can be detected is reached when the intensity of the "signal" (the sound received from the target) equals the intensity of the "noise" (the sound received from sources other than the target). Stated more technically, the target can be detected as long as the signal-to-noise ratio exceeds unity. It follows that extension of search range must be sought through development of equipment that increases the signal-to-noise ratio over and beyond that given by present submarine listening equipment.

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4. The signal-to-noise ratio is influenced by several factors, of which the more important are:

a. Character of the sound generated by the target.

b. Attenuation of the target sound in transit.

c. Character and origin of the various components of the local sound field to which the receiver is exposed.

d. Directivity, location, and sensitivity of the receiver.

e. Distortion of the signal path from linearity in the vertical plane.

f. Response of the receiver-amplifier and of the sound reproducer as a function of frequency.

Extension of the search range must be sought through a consideration of and a proper weighting of the part played by each of these factors.

5. Sound generated by the propellers forms the major part of the total sound output from the target. Analyses of the propeller sound of surface ships steaming at standard speed show a substantially continuous spectrum extending throughout the audible and far into the supersonic range of frequencies. The intensity tends toward a broad and somewhat indefinite maximum within the frequency band 0.8 - 3.0 kilocycles.

6. Attenuation of the target sound in transit results from absorption due to the viscosity of the medium and to scattering caused by its lack of homogeneity. The loss from both causes can be roughly expressed as proportional to the three-halves power of the frequency. Loss of signal intensity in transit is of little consequence at the shorter ranges employed in attack procedures, but such loss becomes a potent factor in determining long-range detection limits.

7. The character of the local sound field to which a receiver mounted forward of the conning tower is exposed while the submarine makes from 4 to 6 knots submerged differs from the sound generated by the target in three respects as follows:

a. The overall intensity is decidedly less.

b. The intensity vs frequency curve gives more emphasis to the sonic than to the supersonic part of the spectum.

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c. The maximum intensity tends to fall within the frequency band 0.1 - 0.3 kc, which is noticeably lower than the corresponding band for the sound from the target.

8. A considerable part of this sound field originates at the propellers, which generate relatively weak supersonic components because cavitation does not occur within this low speed range. The propeller sound reaches the receiver mainly by three paths; a) by refraction around the hull, b) by reflection from the sea surface, and c) by reflection from the sea bottom.

9. The portion of propeller sound refracted around the hull arrives from a direction astern and emphasizes the low frequency end of the propeller spectrum. This component, for a top-side mounted receiver, is relatively weak as compared with the surface-reflected component. It is also weak as compared with the bottom reflected component for a keel-mounted receiver except when operating in deep water.

10. The reflected components traverse a vertical plane that includes the keel. They arrive at the receiver from a direction astern of the vertical that depends on the distance between the reflecting surface and the ship's hull in accordance with the relation:

$$\tan \varphi = b/h \qquad (1)$$

where (φ) is the angle which the surface or bottom-reflected component of the propeller sound makes with the vertical, (b) is half the distance separating the propellers and the receiver, and (h) is the vertical distance from the submarine to the reflecting surface.

11. In practice (b) approximates 100 feet. Therefore, at shoal submergence (φ) approximates 45°. for the surface-reflected component, and at deep submergence -- say 400 feet -- this angle shrinks to about 15°. It may be noted that the surface-reflected components play an important part in determining the character of a receiver best suited for the subject purpose, because reception of these relatively intense surface echoes must be avoided to minimize the noise background.

12. The local sound field to which the receiver is exposed also contains components generated by the flow of water across the vented decking, bow planes, uprights, and the receiver dome or housing, together with hull-radiated sound generated by auxiliary machinery. The points of origin and the intensity of these somewhat random components of the local sound field varies from ship to ship. They can be controlled within limits through proper hull design and their influence minimized by proper form and location of the receiver.

13. These considerations lead to the conclusion that at long ranges the ratio at the receiver of the intensity of the sound field from the target to that of the locally generated sound field increases as the pitch of the reception band is lowered, and that the maximum value occurs well down in the audible range, probably below 1000 cps. This ratio of intensities, which equals the signal-to-noise ratio for a non-directive receiver, influences but, as will be seen, is not a prime factor in determining the signal-to-noise ratio for a directive receiver.

14. The signal intensity for a directive receiver does not differ greatly from that of a non-directive receiver employing elements of like sensitivity. But the weakened response of a directive receiver to all components of the local sound field that fall without its directive pattern reduces the noise, and hence increases the signal-to-noise ratio over that given by a non-directive receiver. Thus a question arises as to the practical limits to which the signal-to-noise ratio can be increased by sharpening the directivity of the receiver.

15. The directive pattern of a sound receiver is a function of the wave length (λ) and of the geometric form and dimensions of its sensitive receiving area. The well known pattern for a circular receiving area consists of a central conical beam surrounded by rings or "side lobes" over which the intensity averages some 17 or more db less than the axial intensity of the central cone. Obviously the limit of directivity of such a receiver is determined in practice by the limits to which the angle subtended by the axis and an element of the conical beam can be reduced. This angle (θ) conforms to the relations:

$$\sin \theta = 0.62\ \lambda/r = 0.62\ v/n \cdot r \qquad (2)$$

Where (r) is the radius of the receiver face, (v) is the velocity of sound in sea water, and (n) is the frequency in cycles per second of the sound. Substituting 4800 ft/sec. for (v) gives the very approximate relation:

$$\sin \theta \approx 3000/n \cdot r \qquad (3)$$

where (r) is expressed in feet.

16. Inspection of this relation shows that (r) becomes impractically large at the lower frequencies. Even when sin θ is given its maximum value of unity or, in other words, when the receiver has only hemispherical directivity, a frequency (n) no lower than 600 cps calls for a circular receiver face 10 feet in diameter. It follows that at the lower frequencies the directivity of the receiver becomes ineffective

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in determining the signal-to-noise ratio and inadequate for determining the bearing of the target because of the dimensional restrictions imposed by practical considerations. Thus, the question arises as to the maximum receiver dimensions permitted by practice.

17. A consideration of the possibilities of improving the signal-to-noise ratio by proper location of the receiver answers this question. The range of bearings (relative) through which search is normally conducted lies forward of the beam of the ship and more probably within 72 degrees of the bow. Our consideration of the nature and origin of the local sound field shows that most of the components are directed from abaft the beam. If, therefore, the receiver were located at the bow, all of the local sound field except the component generated along the receiver housing itself would reach the receiver from a direction astern of the bearing range through which search is conducted. Under such conditions, the signal-to-noise ratio of a circular faced receiver utilizes to full advantage the directivity feature, even though the directivity of the receiver is not high. This desideratum holds only for a beam type of projector. A linear array of sensitive elements as employed by the so-called MB and JP types of receivers is receptive to all sounds directed perpendicular to the linear axis and hence is sensitive to the surface-reflected components of the propeller sound and of other components of the local sound field. It is therefore concluded that the receiver should be a beam type and mounted as far forward as practice permits.

18. This condition is best met by locating the receiver over the bow buoyancy tank. And to assure protection from the elements in this exposed position when running on the surface the receiver mounting should be retractable. A survey of the shape and dimensions of the bow buoyancy tank of our submarines indicates that a retractable housing 30" in diameter can be accomodated. This will permit using a receiver with an active circular face at least 24" in diameter. This figure may be regarded as representing about the maximum receiver dimensions permitted in practice. Moreover, it will be seen that a larger dimension should not be expected to net a worthwhile gain.

19. The directivity of such a receiver as a function of frequency is given by substituting (1') for (r) in equation (3). Starting at hemispherical directivity where sine (θ) equals unity, the frequency (n) proves to be 3000 cps, a value that falls within the upper limits of the frequency band of maximum sound output from the target. Experience indicates that the bearing of a target can be determined within about $\pm$ 15° by receiving a frequency band centered at this frequency and setting on maximum intensity alone, and to within $\pm$ 2°

by use of the NRL type of BDI. The corresponding limits for 10, 20, and 30 kilocycles are approximately $\pm 6^{\circ}$, $\pm 2^{\circ}$, and $\pm 0.5^{\circ}$ when settin on maximum intensity alone, and one fifth of these respective values when the BDI is used for final adjustment of the setting. These figures are theoretical, and do not include errors that may result from faulty training mechanism.

20. The limiting range to which a target can be detected is independent of the sensitivity of the receiver for sensitivities beyond the point where the background noise can be heard or registered. This fact becomes obvious when one considers that increasing the sensitivity affects both the numerator and the denominator of the signal-to-noise ratio in like proportion. The modern high-gain amplifier permits reception of the noise background at speeds as low as two knots with a receiver of medium to even of low sensitivity. The flat frequency response of such a receiver raises the hope that a single receiver can serve for both long range search at the lower frequencies, where a high degree of directivity is unnecessary, and for attack at the higher frequencies, where the resulting higher directivity is required. The development of such a broad band receiver is under way.

21. The signal intensity becomes a maximum when the active face area of the receiver is adjusted to parallelism with the wave fronts of the sound received from the target. It follows that the signal-to-noise ratio becomes a maximum, other things being equal, when the receiver is so adjusted. Since the submarine normally operates in a plane below the target and the oft-present negative vertical temperature gradient bends the signal sound path downward, it follows that the receiver must be trainable in both the vertical and horizontal planes.

22. Influence of the receiver amplifier in determining the signal-to-noise ratio lies primarily in its ability to select the frequency band of reception. The character of the sound generated by a target ship depends on the type of ship and upon its speed. Large, slow-moving ships tend to emphasize the low frequencies while smaller ships, and especially high-speed ships, accentuate the higher frequencies. The frequency band giving the maximum signal-to-noise ratio may vary considerably with the class of ship, the speed, and the sea conditions. Thus the receiver-amplifier, through tuning or other means, should be capable of readily selecting the frequency band that gives the most favorable signal-to-noise ratio at the longer search ranges irrespective of the character of the sound generated by the target. The range of tuning should also carry through to the higher frequencies employed in attack procedure.

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23. These considerations of ways and means of improving the search range of our submarines lead to the following conclusions:

(a) The sound equipment must provide for beam-type directive reception of target sound pitched as low as about 3000 cps.

(b) About 24" should be considered a minimum for the diameter of the active circular face of the receiver.

(c) The receiver should be retractively mounted as far forward as practical in the bow buoyancy tank.

(d) The receiver mounting should provide for both train and tilt.

(e) The receiver-amplifier must provide for selecting, by tuning or otherwise, a reception band giving optimum signal-to-noise ratio.

24. The so-called capsule type of receiver, which aims to meet the requirements of subheads a, b, c, and d, may be described briefly as consisting of a trunion-supported 24" circular receiver mounted in the top half of a capsule-shaped housing, with tilt, train, and selsyn repeat-back motors mounted in the lower half of the housing. The multiple-lead cable from the housing may terminate on the control units at any desired remote location.

B. Strengthening the Attack

25. The present emergency has emphasized the need for directing an attack without exposing the periscope. This calls for supplying the Torpedo Data Computer with more accurate and continuous sound range and bearing of the target. The projector equipment is designed primarily to serve this purpose.

26. Both theory and practice indicate that an average azimuth bearing deviation not to exceed 10 minutes can be conservatively expected from the combination of a vertically-split 24" circular receiver and an NRL type of BDI. Recent tests, using the BDI with a 15" receiver, have shown an average deviation of 12 minutes, which figure includes such errors as obtain in the train and repeat-back systems. Other things being equal, the average deviation given by the 24" receiver should equal about 5/8 of this figure, or 7.5 minutes.

27. The range to the target can be determined acoustically by accurate measurement of the time interval between transmission of a signal and return of its echo from the target, or by triangulation. While echo ranging is standard antisubmarine practice, it has two inherent weaknesses that render this method of ranging less desirable and less

effective for pro-submarine use. First, the signals employed for echo ranging might be intercepted and thus lead to successful evasion tactics by the target, and/or expose the submarine to the hazard of attack. And, second, the unfavorable signal-to-noise ratio caused by directive reception of the propeller sounds of the target may reduce the echo range to impractically short limits in the case of extremely noisy targets.

28. The echo-ranging equipment that is under development for the subject purpose employs an impulse type of signal that is too short to permit heterodyning to a clear audible tone. The reception of such a signal by the target is not easily recognized because it is largely devoid of character. The click-like response in the receiver tends to merge with the random irregularities of the noise background.

29. While it cannot be claimed that the use of very short signals for echo ranging eliminates the possibility of interception by the target, it can be stated that carefully conducted tests, wherein the target was provided with modern sound-detecting equipment, have proved that disclosure of the presence of a submarine through its use of short-signal single-ping echo ranging at random intervals is very unlikely. And it may be noted that a single ping is sufficient to give the target range, within the limits of echo ranging, because the receiver can first be properly directed at the target by focussing on the propeller sounds. A possibility of improving the signal-to-noise ratio by echoing from the wake immediately astern of the target will be considered later.

30. The use of very short signals, in addition to improving security, permits of safely driving the sound generator at peak power inputs that would prove ruinous if prolonged, and of generating signals having peak intensity well beyond the limit normally set by cavitation. Preliminary tests indicate that such short, intense signals may be expected to give ranges up to 2500 yards providing the target is not abnormally noisy and the water conditions are favorable.

31. Tests have also proved that a persistent-vision cathode-ray tube provided with a circular range sweep, with provision for keying the signal at the zero point of the range scale, is superior to the chemical recorder for determining the range from a single ping. The development of such echo-ranging equipment for the subject purpose is well advanced. The 24" receiver serves as the projector for this equipment.

32. Two procedures for determing the target distance by triangualtion may be noted. The first and preferred method, as shown in Fig. 1, employs two receivers, one mounted well forward and the other aft along the keel line.

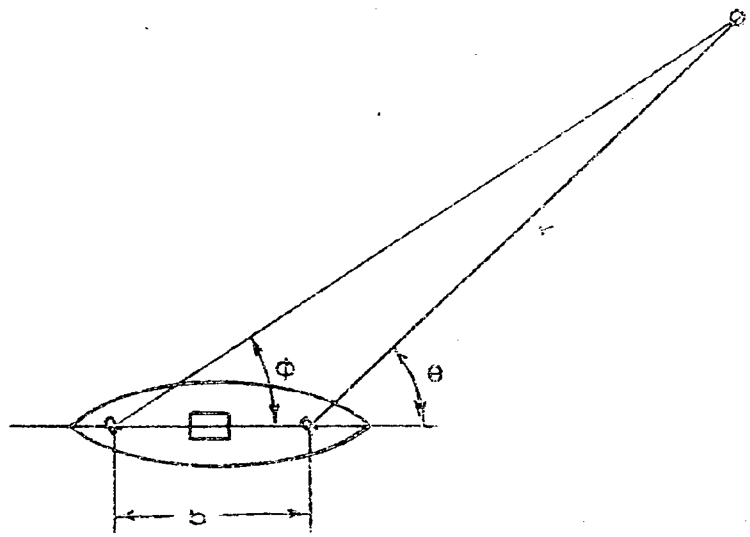

FIGURE 1

The spacing between the two receivers (b), the relative bearings of the target (θ) and (φ) from the location of the forward and aft projectors respectively, determine the range (r) in accordance with the relation, -

$$r = b \cdot \sin \varphi / \sin (\theta - \varphi) \qquad (4)$$

The second method, as shown in Fig. 2,

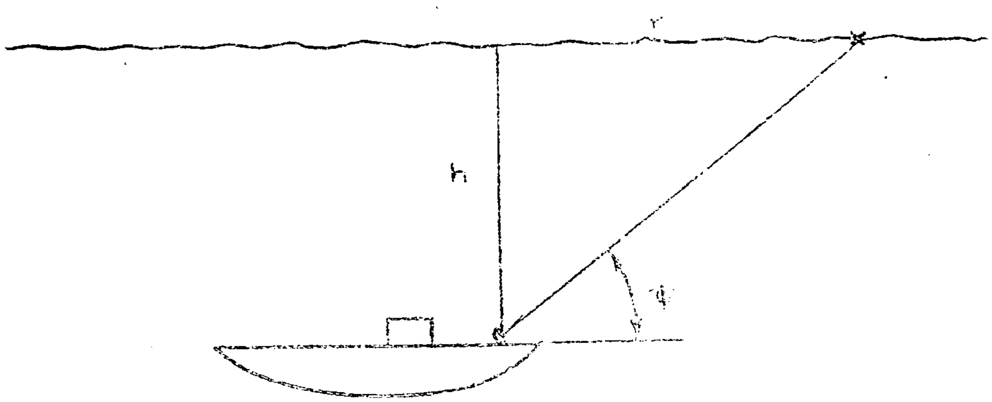

FIGURE 2

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uses the depth of submergence (h) as the base line. This distance, and the measured angle (ψ) subtended between the horizontal and a line directed at the target, determine the range (r) in accordance with the relation:

$$r = h \cdot \tan (\pi/2 - \psi) \qquad (5)$$

33. It may be noted that the capsule type of receiver in combination with the NRL proportional BDI can serve effectively for both methods, since it measures both horizontal and vertical angles with a high degree of accuracy. The second or stern-located receiver can be installed without displacing or adding to the wiring, fixtures, or equipment within the hull, since the capsule receiver has no mechanical parts that enter the hull. The control cables can be run outside to the control point and the same receiver-amplifier, BDI, and train controls that are provided for the forward receiver can serve for both. In short, inclusion of the two-receiver method of ranging adds nothing to the already crowded conditions inside the submarine. The desideratum does not hold for the second method, which obviously requires that the receiver shall be accurately stabilized.

34. The operational procedure for determining range by the second or one-projector method calls for accurate measurement of the one angle (ψ) and recording the simultaneous depth of submergence (h). The procedure for the two-receiver method calls for a moderately accurate measurement of (θ) and an accurate measurement of the difference between (θ) and (φ). This procedure is simplified by coupling the two receivers to a single train control with a differential train in the line to the aft receiver. The system is adjusted so that the two receivers are directed to parallelism when the differential is set at zero. The operator first trains the forward receiver on the propeller sounds of the target and then adjusts the differential until the responses of both receivers are aligned on the BDI when the receiver-amplifier is automatically switched from one receiver to the other from 5 to 10 times a second.

35. The differential train measures directly the difference between (θ) and (φ) when their alternative responses are in alignment on the cathode-ray screen. The proportional deflection feature makes this true whether or not the line is centered on the screen. Thus the operator can concentrate on aligning the responses of the two receivers on the screen without at the same time worrying about the angle (θ). When adjustment for alignment is accomplished he can then concentrate on centering the line to measure (θ) accurately. Thus from the standpoint of simplicity of operation neither method offers marked superiority over the other.

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36. Distortion of the sound path from linearity and misalignment of the sound-receiving equipment may introduce serious range errors in the one-receiver determinations. And experience has proved that such distortion is magnified in the vertical plane by oft-present and unpredictable vertical temperature gradients. The errors due to misalignment can be minimized by providing convenient checks, but the unstable warping of the sound paths by temperature gradients forms a serious objection to the one-receiver method of ranging that has yet to be satisfactorily overcome.

37. The two-receiver method avoids both of these sources of error. The distortion of the sound path in the horizontal plane is usually negligible, but, even if it were not, since the path distortion to each receiver will be substantially identical, and since the direction of each is measured by the same receiving equipment, the errors introduced by path distortion or misalignment in the measurement of each angle cancels out in the process of obtaining the difference angle. Herein we find a convincing argument in favor of the two-receiver method of ranging.

38. Each method obviously becomes inaccurate and unreliable under certain conditions. Inspection of Fig. 1 shows that the two-receiver method fails entirely when the target is dead ahead. In practice this method is not considered reliable when the target bears within 30 degrees of the bow or stern. It may be noted, however, that the two-receiver method works equally well at all depths. The one-receiver method obviously fails entirely when the submarine is surfaced. In practice this method is not considered reliable for depths of submergence less than about 200 feet. It may be noted, however, that the one-receiver method is not dependent on the relative bearing of the target, except perhaps for directions across the conning tower.

39. Thus it appears that the method best suited for determining target range may be any one of the three described, depending on the conditions that obtain. Echo ranging is undoubtedly the most accurate, particularly at ranges beyond about 1000 yards, but it lacks the desirable feature of supplying continuous range data and may fail to give the required ranges on unusually noisy targets. The triangulation methods, however, work best on noisy targets and are capable of supplying continuous range data, but, as noted, each triangulation method becomes inoperative under certain conditons, and both tend to become impractically inaccurate at the longer ranges.

40. Since the addition of a stern-mounted capsule projector is all that is required to provide acoustically for ranging by any one of the three methods, it is proposed to make such an addition a part of the acoustical equipment for submarines until and unless service experience proves a stern-mounted receiver to be superfluous.

41. An interesting by-product of the short-pulse echo ranging in combination with the proportional-deflection type of BDI should be mentioned which may prove useful for determining the course of a target or for navigating through channels or along shore lines. The proportional BDI of NRL in reality is a scanning device that shows, on a horizontal sweep across the cathode-ray screen, the angular bearing with respect to the projector axis of all signal echoes arriving within the angular spread of the projector beam while simultaneously the horizontal sweep line is deflected vertically at a constant rate. Therefore, the vertical or time sweep, which starts from zero at the instant the signal pulse is transmitted, gives the range, and the screen response along the horizontal scan gives the bearing, of all returning echoes. It follows that difference in range and bearing of the various reflecting elements of a horizontally large target should reproduce its contour on the BDI screen.

42. This expectation has been realized. Preliminary tests have shown that the screen response to signal echoes from wakes, reefs, and shorelines give their range and directional trend with considable accuracy. In the case of wakes, determination of their trend gives the course of the ship when the wake was laid to within about plus or minus 10 degrees. The screen response to signals directed forward may aid navigation through tortuous passages by giving advance notice of necessary changes in course.

C. Detecting and Locating Small Objects (Mines and Mine Fields)

43. The detection and location of small objects such as mines and mine fields calls for discrimination between two echo responses that differ but little in bearing or range. In other words the equipment must possess a high degree of resolving power as regards both bearing and range.

44. Both theory and practice agree that an object can reflect back a signal echo when and only when the dimensions of the reflecting area are large as compared with the wave length of the signal. The relatively small dimensions of mines and the disproportionately small reflecting area resulting from their spherical or cylindrical shape set the signal frequency for mine detection well within the supersonic range. Resolving power requirements, as regards bearing, are fully met throughout the supersonic range by the 24" capsule type of projector.

45. Two objects at different ranges along the same bearing line can be separately identified by echoing, as long as the intervening distance (the range difference) is greater than half the signal length. Thus

the resolving power as regards range may be regarded as inversely proportional to the signal length. The intense impulse type of signal employed for determining target range can scarcely be improved upon for detecting and locating small objects, since it permits individual identification of objects separated by less than 10 yards in range. For this purpose, however, the chemical recorder must replace the c-r tube employed for single-ping target ranging, since a record of continuous pinging aids greatly in the recognition of echoes of small objects, such as mines, from a heterogeneous background by the configuration which they trace on the record. The somewhat less effective keel-mounted projector in combination with the impulse driver must be used for mine detection during surface operations.

D. Detecting Torpedoes

46. The sound field generated by the cavitating propellers of torpedoes is intense throughout a wide frequency band that extends well into the supersonic range. Experience has shown that the sound of approaching torpedoes can be detected on merchant ships, by a rapidly rotating directive receiver, at sufficient range to permit taking evasive action. Since the hazards of torpedo attack are for the most part limited to surface operation, a keel-mounted receiver must be employed for torpedo detection. The cathode-ray tube used for echo ranging can serve to indicate the presence and very approximate bearing of an approaching torpedo by synchronizing the rotation of the deflecting field of the c-r tube with the rotation of the projector, since this tube is not needed for echo ranging when the submarine is surfaced. Relative bearing of received sounds will be indicated on the azimuth scale of the c-r tube.

E. Determining Optimum Escape Procedure

47. A continuous record of the approximate range and bearing of the surface ships engaged in an attack on a submarine should serve to direct the escape proceedure to best advantage. The tiltable forward-mounted 24" capsule receiver, in combination with the BDI set to scan radially on a c-r tube with circular sweep, gives promise of supplying such information to a submarine operating at depths beyond, say, 300 feet.

48. For this purpose, equal top and bottom segments of the 24" receiver are disconnected, thus leaving an active horizontal strip centered vertically across the receiver face. This strip is further split

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horizontally for use with the BDI. The directive receiver pattern of the horizontally elongated active area is obviously fan shaped with the spread in the vertical plane. The sharp azimuthal directivity of the receiver locates by maximum response the relative bearing of all sounds received as the projector rotates about a vertical axis. In practice the bearing is flashed on the persistent screen of the cathode-ray tube, which is provided with an azimuth scale and which has its deflecting coils coupled to rotate in synchronism and in proper phase relation with the projector.

49. The screen response of the BDI, which is connected to scan radially, indicates on a radial scale the vertical angular departure (from the acoustical axis of the receiver) of the bearing of received sounds. Such angular departure added algebraically to the angle subtended between the vertical and the axis of the sound beam gives the angle corresponding to $(\pi/2-\psi)$ of equation (5). Thus the relative bearing of each sound picked up by the continuously rotating receiver is indicated by the position of its screen response along the azimuth scale, and the horizontal range to its source on the sea surface is related to the position of its screen response along the radial scale in accordance with equation (5).

50. The relation between the horizontal range of a surface ship and the response of its propeller sounds on the CRT can be understood by considering Fig. 3

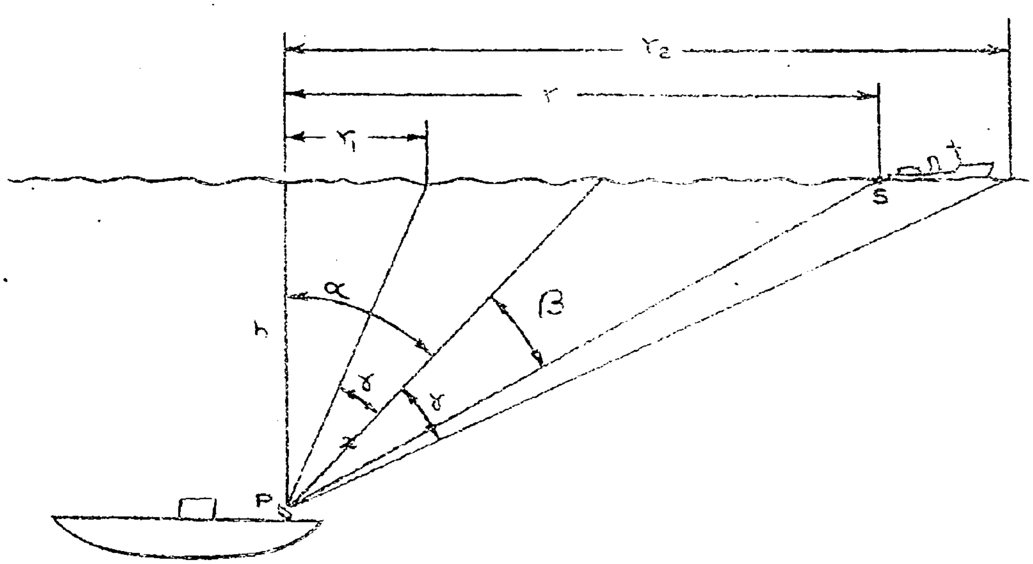

FIGURE 3

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wherein the axis (x) of the projector (p) makes and angle (α) with the vertical (h) and the angles (β) and (γ) represent respectively departure of sound source (s) from the axial direction and the vertical half angular spread of the sound beam. The horizontal range (r), as stated, conforms to the relation.

$$r = h.\ \tan\ (\alpha \pm \beta) \qquad (6)$$

The tilt angle (α) is indicated on the tilt scale of the receiver, and the departure angle (β) on the proportional scale of the BDI. Obviously ranges within the limits (r_1) and (r_2) can be determined without changing (h) or (α) where,

$$r_2 - r_1 = h\ (\tan\ (\alpha + \beta\ )\ - \tan\ (\alpha - \beta\ )) \qquad (7)$$

51. The zonal area bounded by the concentric circles of radii r_1 and r_2 is scanned as the receiver rotates about a vertical axis. And since these radii are proportional to the depth of submergence (h), the radial scale can be calibrated in terms of a standard depth (h) of, say, 100 yards (300 feet), and the range at any other depth will be given by multiplying the scale reading by one percent of the depth (h) in yards. Thus it becomes of interest to consider the nature and extent of the area that can be scanned while the tilt-angle (α) remains constant.

52. First it may be postulated that the range (r_2) shall equal 10 times the depth of submergence (h). Then, -

$$r/h = 10 = \tan\ (\alpha + \gamma) \qquad (8)$$

Thus $\alpha + \gamma = 84.5^\circ$ (9)

From preliminary tests, the BDI can scan a beam spread of at least 60 degrees.

Taking the beam spread (vertical) as 60 degrees gives -

$$2\ \gamma = 60^\circ \qquad (10)$$

$$\therefore \alpha = 84.5^\circ - 30^\circ = 54.5^\circ, \text{ and} \qquad (11)$$

$$\alpha - \gamma = 24.5^\circ \qquad (12)$$

Then at standard submergence of 300 feet (100 yards),

$$r_1 = 100 \tan 24.5^\circ = 47.7 \text{ yards} \approx 50 \text{ yards} \qquad (13)$$

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and $r_2 = 100 \tan 84.5° = 1000$ yards. (14)

53. Thus the spacing of the radial or range scale will accord with a tangent law if the radial sweep is linear, or it may be distorted to approximate linearity by approaching a tangential sweep relation. In either case the zero of the scale will be the center of the screen and the active portion will lie between 50 and 1000 yards. The rotating projector will register on the c-r screen the bearing and range of all surface ships operating between the limiting horizontal ranges of 50 and 1000 yards. The small circular area of radius 50 yards centered directly above the submarine will not be covered by the rotating beam nor will areas outside the 1000 yard range, but these areas can be investigated at any time by properly changing (α) the tilt angle.

54. It may be noted, however, that the record a moving surface ship leaves on the persistent c-r screen indicates the ship's course with respect to the submarine, and that the relative range of two or more surface ships can be estimated at any time in terms of the radial distance of their respective screen responses without considering either the tilt angle or the depth of submergence. Thus it appears hopeful that the moving picture on the c-r screen can serve to direct escape without introducing, during this critical period, delays or distractions incident to determining actual ranges.

II. INTEGRATED EQUIPMENT

55. The foregoing paragraphs have been concerned primarily with the aims and grounds that have determined and directed the present NRL pro-submarine program. A recapitulation follows, giving emphasis to the nature and content of the sonar portion of the complete integrated equipment that includes an improved TDC under development by BuOrd and cooperating radar to be provided by the Radio Division of NRL.

56. The sonar equipment embodies no radical departures from tested and approved practice. A comphrensive search for ways and means that satisfy the several and diverse aims and that conform to practical limitations of weight and space has resulted in a research and developmental program directed to produce three separate and distinct integrants as follows:

a. A projector, having normally a standard conical beam, with provision for hoisting, and for measurably training and tilting the sound beam from a remote control station, but having no mechanical parts which would have to enter the pressure hull and thus preclude installing the projector at any desired location, or which would require, for the cooperating hoist and train gear, any space needed for other purposes. The active circular face area of this projector will be sectioned to permit the use of BDI for accurate adjustment of the train or tilt bearings, and to produce when desired a fan-shaped beam pattern having sharp azimuthal directivity and a vertical spread of about 60 degrees.

b. An echo-ranging system employing a single intense impulse type of signal that is too short to heterodyne to an audible tone.

c. A means of scanning the space within the sound beam of the projector whereby the range and relative bearing of all sound reflecting areas within this space are depicted on a CRT screen through reception of the echoes from a single intense impulse type of signal.

57. The projector requirements promise to be met through development of the "capsule type projector". The sonar equipment, as stated heretofore, includes two such projectors, one mounted as far forward as possible to assure minimum local noise background and the other as far astern as practical to provide a maximum base line for range triangulation.

58. The forward projector is designed to mount in a well extending from the deck to the bottom of the bow buoyancy tank. Hoisting and lowering of the capsule is accomplished hydraulically. Such a mount obviously cannot be employed for the stern-located capsule for lack of well space. It is proposed to use a hinge type of mounting at the lower end of the capsule that will permit tipping the capsule to a horizontal position with a protecting barbette during surface operation. The tilting mechanism, which has yet to be designed, will also operate hydraulically.

59. Echo ranging requirements have not been fully met, but researches directed to this end indicate that the capsule projector can safely withstand a four fold increase over the 2500 volt amperes supplied by the present condenser-energized driver. It is estimated that the new driver, which has yet to be constructed, should give consistent and reliable ranges to about 3000 yards under favorable operating conditions. It may be mentioned here that worthwhile increase in range has followed from investigating the relation between useful output and shape of the driving pulse envelope.

60. Preliminary tests indicate that greater echo ranges can be taken on the wake than on the hull of a noisy target because of the resulting smaller contribution of the targets' propeller sounds to the noise background. The angle (θ) which the reflecting wake makes with the projector axis (given by the NRL BDI), the angle (ϕ) by which the projector axis is directed astern of the propellers, the echo range (r) to the wake, and the target range (R) are simply related as shown by Fig. IV

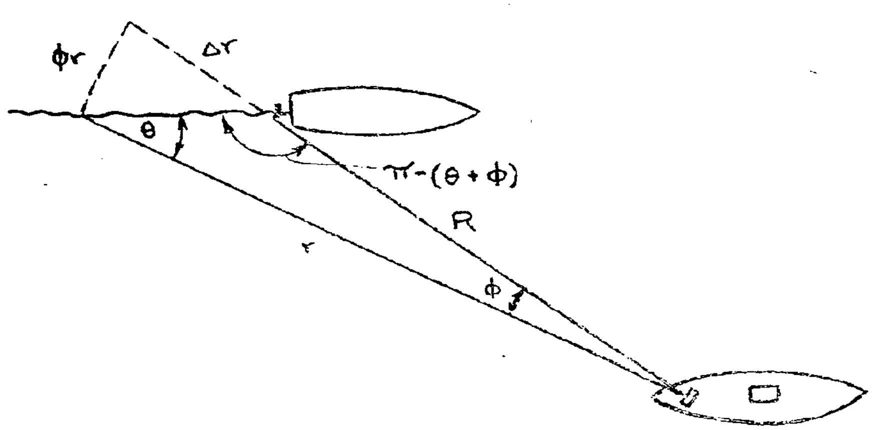

FIGURE 4

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By the law of sines

$$\frac{\sin\theta}{R} = \frac{\sin[\pi-(\varphi+\theta)]}{r} = \frac{\sin(\varphi+\theta)}{r} \quad (15)$$

$$\therefore R = r\cdot\frac{\sin\theta}{\sin(\theta+\varphi)} = r\cdot\frac{\sin\theta}{\sin\theta\cdot\cos\varphi+\cos\theta\cdot\sin\varphi} = \frac{r}{\cos\varphi+\sin\varphi\cdot\mathrm{ctn}\,\theta} \quad (16)$$

Because of the small value of ( ), sufficient accuracy for practical purposes i given by the simplified form:

$$R \approx \frac{r}{1+\varphi\cdot\mathrm{ctn}\,\theta} \approx r(1-\varphi\cdot\mathrm{ctn}\,\theta) \quad (17)$$

61. It may be noted that this procedure of determining target range is of interest for two reasons; it not only promises a desired extension of the echo range, but, of equal or greater importance, it reduces the chances of exposure to the point where more range data can be risked.

62. Tests of numerous schemes for indicating or recording the range as given by a single "pulse ping" have consistently favored the c-r tube with persistent screen and rotated magnetic deflecting field. In practice, the deflecting field is so adjusted that the electron beam scribes a circle with a radius half an inch less than the radius of the screen. The projector is then focussed on the propeller sounds of the target and the receiver sensitivity adjusted to a point where these sounds register faintly on the screen. Such adjustment gives a trace of the propeller sound on the screen about 1/4" wide.

63. The signal is triggered by contacts which are operated by a cam that rotates in phase with the deflecting field of the c-r tube and that is rotationally adjusted to transmit a signal at the instant the deflected electron beam passes zero on the circular range scale. Range determination is initiated by closing a hand key connected in series with the contact points. The design provides for transmission of but one signal for each closing of the hand key.

64. The c-r tube is provided with a hand or TDC operated cursor that can be rotated to center on the persistent screen response to the target echo. The range is read from the subtended point on the range scale. By serving a smemory of the last range, the cursor simplifies determination of rate-of-change-of-range. This information is given by

dividing the range covered in moving the cursor to center on a new target echo by the corresponding time interval. The cursor-indicated ranges are communicated to the TDC, or to other remote points, through synchro-motor coupling.

65. Means have been perfected for scanning the directive pattern of a projector that gives a screen presentation showing the relative bearing of all sound sources located within this pattern, and both the range and bearing of each and every object or surface element within this space that reflects back an echo from a single projector "ping". This development* provides a new means of scanning that promises wide application in the field of submarine acoustics. It differs from the so-called PPI scanning in that it presents the location of all echo targets within the confines of a fixed sound beam, while the ordinary PPI presents the location of echo target swept past by a rotating sound beam. The fixed beam scan thus gives a fine-grained presentation that favors accuracy in bearing discrimination within a limited sector, while the rotating scan covers the whole azimuth, but at a sacrifice of directivity and screen-pattern resolution.

66. An exposé of the basic theory, practical aspects, and operational capabilities of this new scanning sonar development falls outside the scope of this report. A second report devoted entirely to this subject in preparation.

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* NOTE - The device has been recluctantly referred to in this report as the "NRL Type BDI". This nomenclature is both cumbersome and misleading. Laboratory personnel from the start have used the suggestive term "Echo Vision" (E.V.) to designate this equipment. But since the screen picture indicates bearing deviation by depicting the actual location of a target with respect to the axis of the sound beam, the device has somehow become classed as one of the several types of BDI. Such classification is entirely misleading in that it fails to recognize scanning ability, which is the salient feature.

This new development adds a second and useful method and means of scanning a predetermined space that should be recognized as such through a suggestive name. The rotating beam scan has become generally known as "Plan Position Indicator" (PPI). The similar and suggestive nomenclature "Sector Scan Indicator" (SSI) readily identifies the subject sonar device. Adoption of this name is recommended.

III. SUMMARY

67. The purpose of the present nontechnical report is to inform the Submarine Service of the nature and extent of the sonar pro-submarine research and developmental program that is being prosecuted by NRL. The following brief summary may serve to show that the program is well-considered and more comprehensive than is generally known and recognized throughout the Service.

68. The program aims to provide the submarine with sonar equipment that improves search range; cooperates with a new and improved TDC under development by BuOrd to strengthen attack; safeguards the submarine by detecting mines and approaching torpedoes; assists navigation by showing the presence, range and trend of shoals, reefs, and shore lines; and finally helps to direct escape procedure through the aid of a PPI type of scan that depicts the relative bearing, range, and course of the attacking surface ship or ships.

69. The nature of the equipment required to accomplish these several aims has determined the research and developmental program which is dedicated to perfecting three separate devices that integrate to form the complete sonar installation: the capsule type of projector, the elements required for impulse echo ranging, and means for scanning the space within the directive pattern of the sound beam.

70. These three developments have been carried to the point where preliminary tests encourage a belief that all or nearly all the aims of the program will be fairly well met, and that the completed program will provide seriously needed safeguards for our submarines and increase their effectiveness in combat.